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INTERIM REPORT NO. 2

INTEGRATED APPROACH TO METAL FATIGUE

CONTRACT NAS1-3170

Period October 15, 1963 to January 15, 1964

CURTISS-WRIGHT CORPORATION
CURTISS DIVISION
CALDWELL, NEW JERSEY
CODE IDENT. No. 71791

OTS PRICE

XEROX $ 1.60 ph

MICROFILM $ .80

ENGINEERING DEPARTMENT

NO. OF PAGES 10

DATE Jan. 31, 1964

REV. LET.	REVISIONS	DATE

	BY	APPROVED	APPROVED	APPROVED	APPROVED
NAME	J H Redfern	F.A. Stulen	J M Schuh		
DATE	1-31-64	1-31-64	1-31-64		

FORM 1094

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INTRODUCTION

Several formulas have been proposed by the Curtiss Division defining the rate of crack propagation as the result of the application of both alternating and steady loads. Another relation has been proposed for the "fatigue limit" of a crack of a specified length called the "critical dynamic crack length". From these formulas, a general cumulative fatigue damage formula has been derived which defines damage in terms of certain characteristic crack lengths.

Several of the more fundamental formulas are:

1. Critical Dynamic Crack Length

$$f(s_m)\ s^{\beta} \times \ell_d = c$$

This is the proposed formula which states that there is a stress level below which a crack of a given size will not propagate.

2. Crack Propagation

$$\log \frac{\ell}{\ell_a} = k\ f(s_m) \sum_i \phi\ s_i^{\alpha}\ N_i$$

This is the general crack propagation formula for multiple alternating stresses with superimposed steady stress and including the stress-interaction function ϕ. This function will be discussed later. This formula reduces to

$$\log \frac{\ell}{\ell_a} = k \sum_i \phi\ s_i^{\alpha}\ N_i$$

for multiple alternating stresses with mean stress equal to zero. For a single alternating stress the formula reduces to

$$\log \frac{\ell}{\ell_a} = k\ s\ N$$

3. The Cumulative Fatigue Damage Formula, derived from the above formulas is:

$$D = \frac{\log \frac{\ell}{\ell_a}}{\log \frac{\ell_{fr}}{\ell_a}} = \frac{1}{f(s_{mr})\, N_r} \sum_{i} \phi\, f(s_m) \left(\frac{s_i}{s_r}\right) N_i$$

Legend

$f(s_m)$	=	function of mean stress (as affecting crack propagation or critical crack length)
ℓ	=	crack length
ℓ_a	=	initial crack length
ℓ_d	=	critical dynamic crack length
ℓ_{fr}	=	critical length of crack for <u>static</u> failure at the reference (highest) stress in the spectrum
s_i	=	alternating stress value in the spectrum
s_m	=	mean or steady stress
s_r	=	reference alternating stress level
N_i	=	number of cycles at s_i
N_r	=	number of cycles to failure at the reference stress level
D	=	damage (defined by formula)
ϕ	=	stress-interaction function
β, k, α, c	=	material constants defined in the various formulas

The purpose of work being performed under this contract is to evaluate the parameters in the above formulas for one material and to develop the testing techniques required to obtain constants for any material. The following three tests are to be run:

Phase I

Purpose: To verify the hypothesis of the existence of a critical dynamic crack length.

Program: Cracks will be produced in specimens which have a hole drilled in the center of the test area. Specimens will be loaded to a stress well above the endurance limit and run until cracks of the desired length are produced. Crack sizes used would fall into three length groups. Cracks will be measured by visually examining the specimens while the machine is stopped.

Specimens will be run at a stress level (mean plus alternating) below the level at which the cracks will propagate. A specimen will be examined at 10^7 cycles to determine whether progression has occurred, then the stress level will be raised by some predetermined amount, another 10^7 cycles will be run, and the cracks re-examined. These steps will be continued until progression occurs. Three specimens of each of the three crack lengths will be tested to evaluate the critical crack length formula for that mean stress.

This test will be repeated for two additional mean stresses.

Specimens Required: 3 specimens x 3 crack lengths x 3 mean stresses = 27.

Phase II

Purpose: To evaluate the parameters in the crack propagation formula for a single alternating stress.

Program: Cracks of two lengths will be generated as in Phase I above.

Specimens will be run at a mean and alternating stress such that propagation of the crack will occur. Crack length will be continuously measured so that propagation rates can be obtained. Three specimens of two crack lengths will be run at each of three alternating stresses at that mean stress.

This test will be repeated for two additional mean stresses.

Specimens Required: 3 specimens x 2 crack lengths x 3 alt. stress x 3 mean stress = 54.

Phase III

Purpose: To evaluate the hypothesis that the growth of a crack in a specimen subjected to a stress spectrum is equal to the summation of the growths due to the individual stresses, and, to verify the hypothesis of a stress interaction function, ϕ. The exact nature of this function is unknown now, although some experimental programs conducted in recent years give an indication of its nature. One objective of this research is to obtain a quantitative and qualitative evaluation of this function.

Program: Cracks of two lengths will be generated as in Phase I above.

From Phase II part of an SN curve for each crack length at each mean stress will be obtained. Specimens of one crack length will be run at one mean stress at an alternating stress near the low end of the SN curve for that crack length and mean stress. The specimen will be run for a predetermined percentage of the life expected at that stress level. The test will be stopped and the alternating stress increased to a higher level. The specimen will than be run for a predetermined percentage of the life expected at the new alternating stress level. Stresses will be increased and cycles run until failure of the specimen occurs.

Repeat the above test except start at highest stress and step down and then run the test with alternating stresses in random orders.

The crack lengths will be monitored as required to determine interaction effects.

Specimens Required: 3 specimens x 2 crack lengths x 3 specimens x 3 mean stresses = 54.

DISCUSSION

Crack Generation

Cracks were generated in 10 specimens by loading them in the Sonntag testing machine at a steady stress of 50,000 psi and an alternating stress of ±30,000 psi. Attempts to generate cracks in a reasonable length of time at stresses appreciably lower than this were not successful. It is believed that this stress is below the smooth endurance limit for this material; therefore, the condition of the metal at the tip of the crack should be no more cold worked or stressed than would be the case for a crack developed in a smooth part in service.

The length of cracks generated in the ten specimens is tabulated in Table I along with the width, thickness, and area of the specimens. Also tabulated are the hole size and the approximate number of cycles required to generate the crack. The test machine had to be stopped several times during crack generation in order to monitor the crack length, therefore, the number of cycles could only be estimated because the counter on the Sonntag test machine measures time, and an appreciable amount of time is used in bringing the machine up to speed. This effect is negligible for runs of several thousands of cycles, but for the short runs used in the later stages of generating these cracks, the error is appreciable. Variations in hole size and in the edge condition of the holes accounts for the variations in number of cycles required to generate cracks of approximately the same length.

It was possible to control the length of the cracks with reasonable precision. For the nine specimens used to generate the longest cracks, the median length was .0923, the shortest length .0911 and the longest length was .0963. This is an error of less than ±5%. Crack lengths could probably be held closer than this, but such precision is not regarded as necessary.

Specimen Preparation

The first specimen received had the original surface finish of the titanium sheet. It was found impossible to accurately locate the end of the crack with this surface finish. Therefore, the next nine specimens were buffed to a high finish before hole drilling. The specimen drawing has been changed to specify a polished surface in the test area.

Hole drilling on the ten specimens received to date was done by the electric discharge method. As can be seen in Table I the sizes of holes varied from .0064" in diameter to .015". These holes were satisfactory for the large sized cracks generated on these specimens, but would not be good enough to produce cracks of .010" in length as is required to test the effects of very small cracks. Samples of the sheet material were sent to a vendor who mechanically drilled a hole .005" in diameter. This hole will be satisfactory if it is not so cold worked at the surface that a crack will not start at the hole. It is planned to drill only 10 specimens by this method to make certain that the holes will start cracks. Attempts were made to get a hole in the titanium sheet by the electron beam method, but this was not accomplished. If the drilled hole is satisfactory, all holes will be made by this method. If not, the holes will be made by the electrical discharge method and the smaller holes produced will be used to generate the smaller cracks.

Grip Design

During early testing, a failure of one grip took place. Failure started in one of the serrations of the grip beyond the point where the specimen was clamped. These grips were reworked to remove the last two serrations and the area was shotpeened. These reworked grips proved satisfactory during testing at low stress levels, but when stresses were higher and a large number of cycles were accumulated, failures of the reworked grips took place. For this reason, the grip was redesigned so that the volume of metal subjected to bending stresses during testing was doubled. These redesigned grips are now in procurement.

Clutch Operation - Sonntag Test Machine

In order to prevent overload on specimens due to excessive acceleration of the rotating eccentric on starting, the Sonntag test machine is equipped with a friction clutch which is adjusted to slip so that the eccentric reaches syncronous speed 9 to 12 seconds after starting the drive motor. The clutch is not to slip during operation at syncronous speed. During early testing under this contract it was observed that one of the clutches was chattering during operation. This indicated that the clutch was slipping momentarily and then grabbing again. It is believed that when the clutch grabbed after slipping, the eccentric would momentarily be accelerated causing an unknown overload on the specimen for a brief period of time. When this condition was observed, a new clutch was obtained and one clutch was reworked. The reworked clutch worked for a time, but that one then developed noticeable chatter. Another new clutch has been obtained and spare parts are in procurement so that any further clutch failures can be corrected immediately.

Phase I Testing

Results of testing are tabulated in Table II. Under pure alternating load only two specimens went to failure because of grip failures. Comparing these two, the specimen (F5) with a crack .0353" long failed at only a slightly higher stress than the specimen (C-1) with a crack .0915" long. This is believed due to the fact that there was known chattering of the clutch during testing of the specimen with the shorter crack. This could result in a stress higher than the ±33,000 psi shown in Table II.

The alternating stress of ±32,000 psi which failed specimen C-1 may also be in error. The clutch used for this test was reworked and there was no chatter evident to the ear during this run. However, another specimen (J-3) with a crack of approximately the same length survived 10^7 cycles with alternating stresses of ±32,000 psi, ±34,000 psi and

3.254×10^6 cycles at a stress of ±36,000 psi before a grip failure stopped the test. This specimen was run with a new clutch. This indicates either that specimen C-1 was overloaded by the reworked clutch or there is considerably more scatter in the fatigue strength of cracked specimens than was anticipated at the start of the program. Continued testing will establish the amount of scatter to be expected and will thus check the validity of the results obtained on specimen C-1.

Selection of a mean stress was first made by estimating the modified Goodman diagram by drawing a line between ±36,000 psi alternating stress on one axis and the tensile strength of the material on the other axis. This diagram indicated that a mean stress of 50,000 psi could be used with an alternating stress slightly over ±20,000 psi. However, when a specimen was tested at 50,000 psi mean and ±18,000 psi alternating, it failed after 16,000 cycles. Another specimen tested at the same mean stress and an alternating stress of ±12,000 psi failed after 36,000 cycles.

At first it was thought that a bad clutch might be causing these early failures, but published data on other titanium alloys indicated that the stresses might be too high. This data indicated that at a mean stress of 40,000 psi, notched titanium alloy specimens would survive 10^7 cycles at an alternating stress of ±10,000 psi. Therefore, a specimen was tested at a mean stress of 40,000 psi with an alternating stress of ±6,000 psi. Failure took place after 316,000 cycles. Another specimen was tested with the 40,000 psi mean stress at alternating stresses of ±2,000 and ±3,000 psi. The specimen survived 10^7 cycles at each alternating stress and is currently under test at an alternating stress of ±4,000 psi. Tests at the 40,000 psi mean stress have all been performed with a new clutch.

Photographic Method of Measuring Crack Propagation

For Phase II testing, crack propagation will be measured photographically. For this purpose, a 70mm Beattie Coleman sequence camera has been ordered. A timer has been procured so that cracks can be photographed at regular intervals during the life of a specimen. The timing device will open the shutter of the camera. When the shutter is opened, a relay in the camera will close. This relay will be in series with a switch operated by the drive shaft of the Sonntag test machine. This switch can be timed to a specific location of the drive shaft and will close once every cycle of the machine. Current going through the switch and the relay on the camera will fire an electronic flash gun thereby exposing the film in the camera. The timer will close the shutter of the camera which will then automatically advance the film for the next exposure. The timer will hold the shutter open for about 1-1/2 seconds. During this time, there will be about 45 closings of the switch on the drive shaft of the Sonntag machine. However, the recycling time of the electronic flash gun will be in the neighborhood of 10 seconds; therefore, only one flash of light will occur during each opening of the shutter.

TABLE I

GENERATION OF CRACKS

SPECIMEN	THICKNESS INCHES	WIDTH INCHES	AREA SQUARE INCHES	HOLE DIAMETER INCHES	APPROXIMATE CYCLES AT 50 KSI ±30 KSI	CRACK LENGTH INCHES
F-5	.044	1.001	.044	.0070	9,000	.0353
A-12	.043	1.001	.043	.0064	30,500	.0947
C-1	.044	1.002	.044	.0069	28,000	.0915
D-8	.042	1.002	.042	.0080	28,500	.0920
E-11	.041	1.002	.041	.0102	29,000	.0963
G-13	.043	1.001	.043	.0069	17,000	.0952
I-6	.043	1.003	.043	.0064	31,000	.0923
J-3	.043	1.002	.043	.0150	21,500	.0918
K-9	.042	1.002	.042	.0075	24,000	.0928
M-2	.041	1.002	.041	.0118	22,000	.0911

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TABLE II

TEST DATA - PHASE I

SPECIMEN	CRACK LENGTH INCHES	MEAN STRESS KSI	ALTERNATING STRESS KSI			NO. OF ALTERNATING STRESS STEPS	CLUTCH CONDITION	REMARKS
			START	STRESS INCREMENT BETWEEN STEPS	FINAL			
F-5	.0353	0	± 15	3	± 33	7	Chattering	Failed after 163,000 cycles at ±33 KSI
C-1	.0915	0	± 18	2	± 32	8	Reworked	Failed after 938,000 cycles at ±32 KSI
K-9	.0928	0	± 24	2	± 32	5	Reworked	Grip failed after 1,220,000 cycles at ±32 KSI
M-2	.0911	0	± 26	-	± 26	1	New	Grip failed after 1,245,000 cycles at ±26 KSI
J-3	.0918	0	± 26	2	± 36	6	New	Grip failed after 3,254,000 cycles at ±36 KSI
I-6	.0923	50	± 18	-	± 18	1	Reworked	Failed after 16,000 cycles
D-8	.0920	50	± 12	-	-	0	Reworked	Failed in tension when preload controller failed
E-11	.0963	50	± 12	-	± 12	1	Reworked	Failed after 36,000 cycles
A-12	.0947	40	± 6	-	± 6	1	New	Failed after 316,000 cycles
G-13	.0952	40	± 2	1	-	-	New	Still running. Survived 10^7 cycles at ±2, ±3